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UPGRADE AND TESTS OF THE SPS FAST EXTRACTION KICKER SYSTEM FOR LHC AND CNGS

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Abstract

A fast extraction kicker system has been installed in the SPS and successfully used in extraction tests in 2003. It will serve to send beam to the anticlockwise LHC ring and the CNGS neutrino facility. The magnets and pulse generators have been recuperated from an earlier installation and upgraded to fit the present application. Hardware improvements include diode stacks as replacement of the previous dump thyratron switches, a cooling system of the magnets, sensors for its ferrite temperatures and magnetic field quality assessment. In preparation of the future use for 450 GeV/c transfer to LHC and double batch extraction at 400 GeV/c for CNGS the tests comprised extractions of single bunches, twelve bunches in a single extraction and single bunches in a double extraction. The measured kick characteristics of the upgraded system are presented, along with a discussion of Pspice simulation results. Further improvements will be discussed which are intended to make the system comply with the specifications for CNGS.

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INTRODUCTION

The previously existing MKE fast extraction kicker system (as used since the late 70's until 2000 in the Super Proton Synchrotron (SPS)) has been renewed to meet the LHC and particularly the CNGS specifications, see Table 1 [1]. The fast extraction in SPS Long Straight Section 4 (LSS4) is common between the LHC and CNGS. In 2006 for CNGS double batch extraction per SPS-cycle is foreseen; the field rise-, fall-time and flattop length are very critical in this case. The field has to increase from 0 to B_{max} or vice versa in less than 1.1 µs; the non-populated space between two (10.5 µs long) batches of 2100 bunches each. For extraction towards LHC only one extraction per SPS-cycle with a usable flattop length of 7.9 µs is required. Since only one third of the SPS ring will be filled there are no severe restrictions on the kicker rise- nor fall-times, however, the flattop ripple requirements are more stringent.

SYSTEM OVERVIEW

General Layout

The fast extraction kicker system is a characteristically terminated travelling wave system, powered by a resonant charging circuit [2]. Fig. 1 shows schematically the kicker installation in SPS LSS4 / ECA-4.

Measures are taken to protect the extraction channel septa which deflect the extracted beam further into the

Table 1: SPS LSS4 MKE kicker parameters

	LHC*	CNGS
Energy [GeV/c]	450	400
Total system deflection angle θ [mrad]	0.48	0.54
# MKE-L (large aperture) magnets	3	3
# MKE-S (small aperture) magnets	2	2
Magnet length [m]	1.674	1.674
2-98%Rise time [µs]		< 1.1
Operating voltage [kV]	46.9	47.0
Induction field MKE-L [T]	0.0826	0.0828
Induction field MKE-S [T]	0.0904	0.0905
Usable flat top length [µs]	7.9	10.5
|Flattop ripple (overshoot)|	< 1%	< 2%
98-2% Fall time [µs]		< 1.1

*: for protons

TT 40 / TI 8 transfer lines. If a switch "missing" or "erratic" occurs, all clipper switches are triggered to empty the PFN's and thereby indirectly protect downstream SPS (septa) elements [3]. One of the eminent problems which have been resolved in the upgrade of the previous system, by better decoupling the clipper switch thyratron power trigger inputs, is the frequently occurring clipper switch erratics. In addition, to reduce long term costs and improve lifetime and reliability a system (configuration) has been successfully developed in which the thyratron (gas discharge) "dump" switches have been replaced by 72 kV semiconductor power diode-stacks

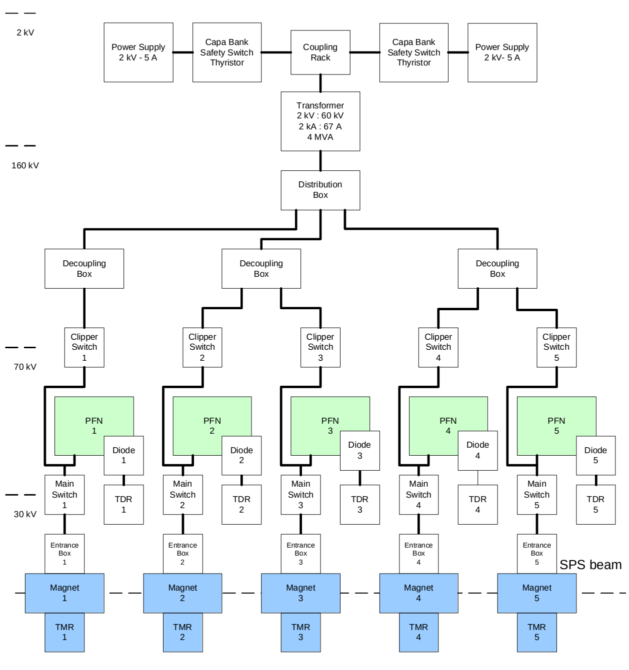

Figure 1: Schematic MKE kicker installation layout in SPS LSS4/ECA4. Modified components are indicated by a filled pattern.

(consisting of 6x6 2 kV series diode-units with 36 1 MΩ series' resistors in parallel for a uniform voltage distribution).

Kicker diagnostics

The magnetic field was measured in a non-modified MKE-S magnet, with an inductive probe (which also serves as a good field calibration reference). For the upgraded extraction kicker magnets, two capacitive pick-ups per magnet have been installed also enabling "kick" measurement when installed in the SPS machine [4]. These diagnostics give a detailed picture of the "kick" rise, fall and (flattop) pulse length times including the magnet filling time, as well as the overshoot.

Cooling

As part of the extraction system upgrade, the implemented cooling for the expected significant SPS magnet's ferrite heating was addressed with highest priority. Extensive data with respect to SPS kicker heating were taken [5]. For the proposed LHC and CNGS beam-operating conditions the SPS extraction kickers will be exposed to a much larger beam induced thermal power than before. A solution has been successfully implemented [2, 5, 6]. The MKE extraction kicker system is equipped with *PT100* temperature probes to provide an SPS beam interlock to prevent equipment damage.

MEASUREMENTS AND SIMULATIONS

Reference measurements

The fast extraction kicker system was installed and tested for the 2003 SPS to LHC/CNGS extraction tests.

A representative pulse for the 2003 fast extraction kicker system is shown in Fig. 2. The 1 to 99% rise- and 99 to 2% fall time were 1.0 µs respectively 4.2 µs and the flattop ripple (overshoot) was 11% for a 19 µs kick pulse length. The fall time and overshoot were not meeting the specifications (see Table 1). With the resulting usable batch length this would lead to with 20% less protons on target for CNGS. Further improvements to meet the CNGS specifications were needed and consisted of a rise time optimisation, fall time optimisation and shortening the MKE generator PFN length, as illustrated in Fig. 1 (see also top Fig. 2).

PSpice simulations

Pspice simulations for the MKE extraction kicker system were done. The PFN's and magnets consist of (fourteen respectively seven) transmission line sections as an approximation to an ideal travelling wave impedance of $Z_0 = 10\ \Omega = \sqrt{L_{PFN}/C_{PFN}} = \sqrt{L_{magnet}/C_{magnet}}$. Evaluation of the effects of various parameters showed that it was inevitable to implement magnet damping resistances to comply with the flattop requirements; in series with the magnet capacitances 10 Ω magnet damping resistors were added. To meet the rise time specifications detailed fine tuning of the PFN front cells turned out to be mandatory, as well as

Table 2: Measured extraction kicker system parameters.

	2003	LAB	2004*
Rise time 1-99% [µs]	2.5	1.2	1.1
Fall time 99-2% [µs]	3.8	1.5	1.1
Usable batch length [µs]	2·8.5	2·10.3	2·10.5
|"Kick" pulse flattop ripple| (overshoot)	11%	<2%	<2%
Post "kick" pulse ripple	<20%	<10%	<2%
Maximum operating voltage [kV]	50	20	55

*: including expected damper performance

sorting of PFN capacitor/coil section values. To get an ideal square (fastest) PFN pulse at the magnet entrance a PFN front cell with a capacitance $C_{PFN,\ front\ cell} = 0.5 \cdot C_{PFN}$ in parallel with a series inductance $L_{PFN,\ front\ cell} = L_{PFN}$ and resistor $R_{front\ cell} = Z_0 = 10\ \Omega$) is used. The pulse overshoot could be precisely tuned with the first PFN inductance (optimal $L_{PFN,1} = 1.3 \cdot L_{PFN} = 6.8\ \mu H$). To decrease the pulse "dip" after the first overshoot and further flatten the pulse ripple the first PFN capacitance should be slightly increased (optimal $C_{PFN,1} = 1.15 \cdot C_{PFN} = 60.8$ pF). To improve the fall time behaviour a Terminating Magnet Resistance (TMR) impedance mismatch (increasing the resistor value from 9.9 Ω to 10.7 Ω) should enable overall improvement of the remaining kick component by forcing a zero crossing resulting in the minimum distortion to the bunches in the second batch (after the first batch extraction), see Fig. 2 (bottom) [7]. In parallel the results were implemented stepwise in the prototype (spare) MKE kicker system.

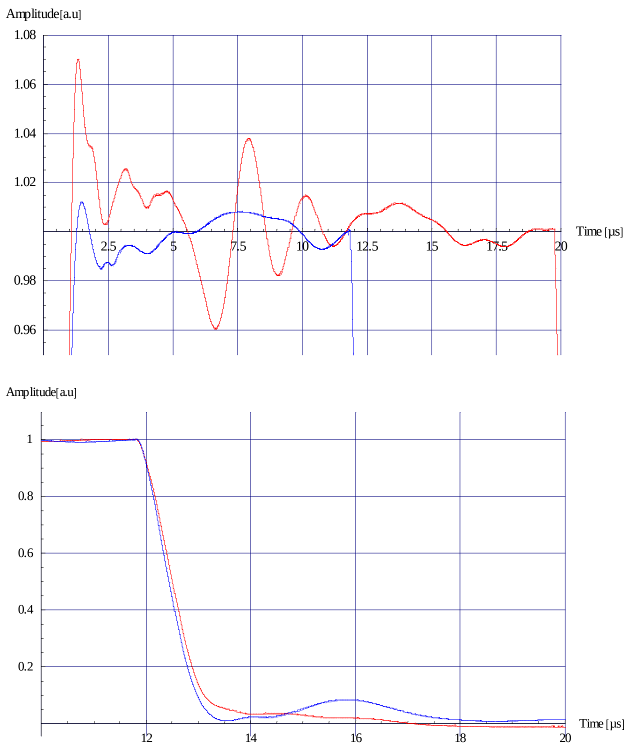

Figure 2: Measured MKE kick pulse characteristics before (2003) (red) and after the modifications (2004) (blue). Note (bottom figure): For comparison the 2003 signal is diplaced to the left by 7.9 µs.

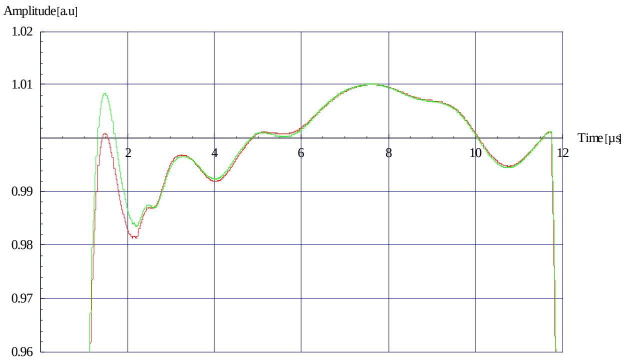

Figure 3: Measured fine tuning of optimised MKE kicker system: $L_{PFN,1}$ = 6.6 µH (green) $L_{PFN,1}$ =6.8 µH (red).

High voltage lab measurements and tests

Also shown in Fig. 2 is the improved kick pulse after optimisation (and implemented modifications for the lab installation), see Table 2.

Figure 3 shows an example of kick pulse fine tuning for $L_{PFN,1}$ = 6.6 µH respectively 6.8 µH.

SPS machine reinstallation + tests

The SPS MKE fast extraction kicker system was modified according to the above mentioned procedure, to reproduce the laboratory results. Fig. 4 shows the measured normalised individual MKE magnet kicks and

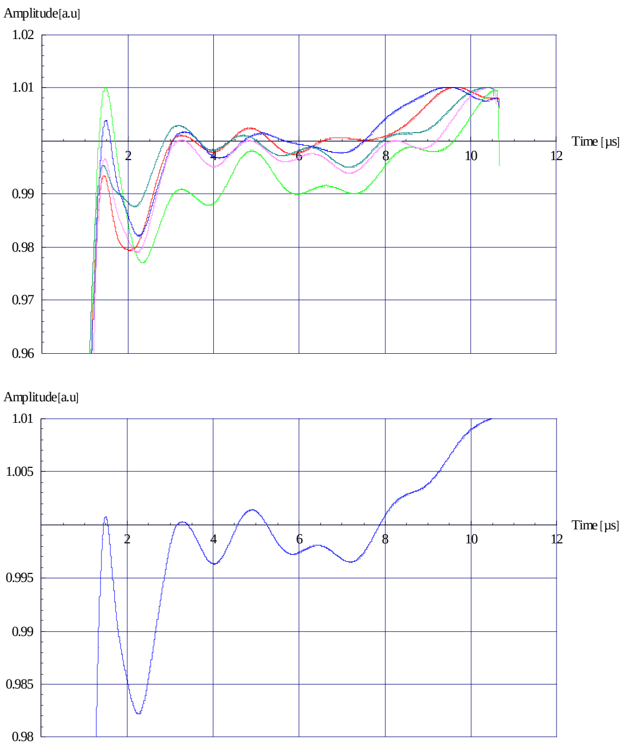

Figure 4: Measured SPS MKE kicks (top) and resulting overall kick (bottom): $t_{r,1\text{-}99\%}$ =1.3 µs flattop ripple < 3%. Note: The TMR's were not yet modified at this moment; increasing the first PFN capacitance is still an option and could be implemented at a later stage.

the normalised resulting overall extraction kick at 10 kV. The modified SPS MKE fast extraction kicker system successfully passed the high voltage re-commissioning pulse tests. Improved clipper switch erratics behaviour (probably due to better (critically) damped reflectionsµ led to an increase in maximum operating voltage up to 55 kV (see Table 2).

SPS machine measurements with beam

In the 2003 extraction tests, the usable double batch length was 8.5 µs. SPS CNGS extraction tests are planned for September 2004. An SPS MD (machine development) test is foreseen to confirm the possible use of the SPS damper to damp the induced second batch ripple of <10 % within 50 ms (= 2155 SPS turns) and thereby reduce the effective fall time from 3.6 µs to 1.1 µs, resulting in a usable batch length of 2*10.5 µs [7]. The aim is to obtain a definitive answer on expected performance by autumn 2004.

CONCLUSIONS AND RECOMMENDATIONS

The implemented fast extraction kicker system modifications have proven successful and are expected to enable a successful double batch CNGS extraction on target in 2006.

Various added diagnostics have proven valuable for increasing the overall system performance.

A solution to the remaining post pulse ripple problem has been proposed and analysed, i.e. using the SPS damper to damp the induced second batch ripple, for which experimental confirmation is expected in SPS MD studies with beam later in 2004.

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